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TESTING THE BEHAVE FIRE PREDICTION AND FUEL MODELING SYSTEM

FINAL REPORT

Testing the BEHAVE Fire Prediction and Fuel Modeling System

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ABSTRACT

Tasks for building and refining custom fuel models are discussed, spanning the range of activities from initial fuel data collection to eventual refinement of fuel models based on fire observations. Emphasis is focused on the sagebrush (Artemisia tridentata)-grass fuels complex, although the procedures are broadly applicable to a variety of fuel modeling situations. For each task, we present results from implementing our recommended procedure and problems encountered.

The tasks incorporate procedures developed previously by other researchers, for example for constructing initial fuel models in NEWMDL. In addition, new details are presented for testing and modifying site-specific fuel models through TSTMDL. An algorithm is presented which should assist practitioners in systematizing calibration efforts, based on discrepancies between field observations and model-based predictions of fire behavior, and use of TSTMDL graphics. The procedures were successful in improving rate of spread estimates from custom models; little success was obtained in improving flame length. Practitioners could apply the proposed refinement techniques to modify inputs from standard fuel models, instead of building initial models with NEWMDL or through extensive inventory. However, considerable judgment and expertise are still required to maintain the integrity of the fire behavior prediction process.

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BEHAVE (Andrews, 1986) has become a standard fire behavior prediction and fuel modeling system. The BURN subsystem is for operational fire behavior prediction. The FUEL subsystem, specifically the NEWMDL and TSTMDL programs, facilitates the construction of tailor-made fuel models for a variety of wildland situations (Burgan and Rothermel 1984). The concept of custom fuel models is not new, but the construction of fuel models tailored to a specific site by fire practitioners is now technically possible with the FUEL subsystem routines. However the procedures for construction, testing, and modification of site-specific fuel models are not straightforward. Although users are comfortable with the existing capabilities in NEWMDL and TSTMDL, more instruction and better procedures are needed.

OBJECTIVES

The overall goal of this study is to evaluate the use of the NEWMDL and TSTMDL programs in building custom fuel models and to test the capability of the BURN program to predict fire behavior while using the custom fuel model. Specifically, the objectives of this study are: 1) to evaluate the use of BEHAVE in building custom fuel models for the sagebrush-grass fuel type;[1] and 2) to develop a process by which the custom fuel models can be adapted in light of comparisons between predicted and actual fire behavior.

PREVIOUS WORK

Until recently, fire practitioners have relied predominantly on the library of 13 fire behavior fuel models presented by Anderson (1982) or developed customized fuel models for specific fuel types (e.g. Rothermel and Philpot 1973, Hough and Albini 1978). However, the BEHAVE system, particularly the FUEL subsystem, provides opportunities to develop fuel models that can accommodate a wide variety of fire management activities (Burgan and Rothermel 1984).

Burgan and Rothermel (1984) define the situations in which a user might rely on the standard 13 models without modification:

a. to illustrate fire behavior of different fuels in general without reference to any particular site;
b. For estimating fire behavior when there are no other fuel models for the area and no time to develop them;
c. when some of the standard models have been found to work well for fuels in an area;
d. for instruction and training about fuels or fire behavior.

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[1]Initially, we had hoped to include consideration of the timber/understory fuel type, but had to abandon this effort since few prescribed burns in northern Colorado-southern Wyoming were planned in this fuel type during the study period.

They go on to elaborate situations when one of the standard 13 models would be used with modifications:

a. changing a grass model from static to dynamic;
b. adding live fuel to a model such as slash;
c. adjusting load and/or depth to better represent local fuels;
d. increasing the heat content of very flammable brush.

Inventory techniques by Brown and others (1982) are useful in the following situations: 1) for fuel appraisal, or whenever it is important to compare the relative differences in flammability between fuels complexes; and 2) for developing fuel models where fuels are relatively uniform and values at risk warrant highly accurate fuel models for fire prediction. Even in these situations, however, there are problems in translating inventory information into fire behavior predictions (Rothermel, Albini, and Hirsch, unpublished).

NEWMDL uses are appropriate under the following situations, according to Burgan and Rothermel (1984):

a. when an estimate of fire behavior is needed but the time and expense of inventory is not cost-effective;
b. for developing a fuel model to produce fire behavior predictions that are consistent with fuels difficult to model by other means;
c. for constructing fire behavior fuel models to mimic the behavior of the NFDRS models used in an area.

TSTMDL is used to modify one of the standard 13 models or a model developed in NEWMDL. Since the fuel modeling subsystem in BEHAVE was developed to be used with minimal field sampling, there will be situations when TSTMDL will aid in adjusting either type of fuel model based on observed fire behavior. This may be particularly necessary, where the user relies on the NEWMDL program to develop inputs to the spread model.

Though widely studied and subjected to recurrent fire treatment, the sagebrush-grass complex has been difficult to effectively model for fire behavior prediction purposes. Britton and Clark (1985) suggest at least 20% canopy cover and 300 kg/ha (267 lb/ac) of herbaceous fuel are needed to ensure successful prescribed burning in sagebrush-grass types. Wright and Bailey (1982) suggest that winds in excess of 20 mi/h are necessary to carry fire in low sagebrush. Bushey (1985) establishes a procedure for developing fire prescriptions in sagebrush-grass, based on desired fire behavior to achieve specific fire objectives.

Brown (1982) cites several difficulties in modeling fuel and fire behavior in big sagebrush (Artemisia tridentata), including the discontinuous and nonuniform fuels found on characteristic xeric sites. Weak relationships between crown area, height, and

bulk density with plant age confounded dynamic modeling efforts based on time. Reasonable success was reported in matching ROS predictions to observations; however, flame lengths tended to be underpredicted by about 50 percent. Frandsen (1983) used literature values to transform woody biomass estimates in sagebrush into three standard fuel size classes. He presents tables relating fuel load by size class to the height and canopy area of the shrub for two subspecies of A.tridentata. However, efforts to translate existing fuel studies into models for fire behavior in sagebrush-grass have not been totally successful.

METHODS

Methods involved visits to planned prescribed burn sites and inventory of fuels, generally by the abbreviated methods described in Burgan and Rothermel (1984). Litter, grass, shrub loadings were most often entered into NEWMDL using total depth by vegetation class. Where time permitted more extensive fuel inventory, fuel loads were directly entered into NEWMDL.

During ignition and fire application, study teams (CSU graduate students) collected fire behavior measurements, using techniques described by Rothermel and Rinehart (1983). Upon return from the field, the fire observations were compared with fire behavior predictions from the BURN subsystem, using custom fuel models generated by NEWMDL. Attempts were made to resolve apparent discrepancies between observed and predicted fire behavior using TSTMDL. Problems encountered in the entire sequence from field data collection to TSTMDL refinements are covered in this report, along with recommendations for future work.

RESULTS AND DISCUSSION

Fuels information was collected on the following prescribed burns:

Burn name	Fuel type
Bates Creek	Sagebrush Grass
Martin-Marietta	Mountain Mahogany Oakbrush Fine Grass Hardwood Litter
Wintersteen	Big Sagebrush,Bitterbrush Squaw Currant, Thimbleberry Wild Rose, Mountain Ninebark, Juniper, Rocky Mountain Maple, Waxflower.
Berry Creek	Sagebrush Grass Litter
Walden	Sagebrush Grass
Bear Tree	Slash Conifer Litter Brush Grass

Even though we intended to focus particular attention on the sagebrush-grass fuel type, we felt that lessons could be learned from modeling and monitoring prescribed fires in other fuel types as well. The remainder of this report focuses on our efforts to build and refine a sagebrush-grass fuel model using the NEWMDL and TSTMDL systems in BEHAVE.

Building and Refining the Sagebrush-Grass Fuel Model

For a variety of reasons, the procedures for building and refining a custom fuel model have not been explicitly delineated previously. Essentially, the construction of models to realistically mimic the complexities of wildland fire remains as much an art as science. The process derived and proposed in this study represents, at best, a prototype framework for constructing custom fuel models. Hopefully, others will be able to use the proposed framework as a starting point to tailor their own efforts.

The proposed process can be divided into six major task categories, each of which provides unique problems and limitations for managers hoping to build their own fuel models. These tasks are discussed below in terms of modeling the sagebrush-grass fuels complex. However, the framework presented should be broadly applicable to modeling fuels in a variety of fuel types. The tasks are:

A. Acquisition of Fuels Data in the Field

B. Creation of Initial Fuel Models in NEWMDL

C. Obtaining Initial Fire Behavior Predictions with the Fuel Models

D. Collection of Fire Behavior Observations

E. Analysis of Observed vs. Predicted Fire Behavior to select one Custom Fuel Model

F. Refinements and Calibrations using TSTMDL

The above process provides a sequential framework for constructing and refining custom fuel models and should produce reasonable modeling results. The remainder of this report focuses on how the above tasks were implemented on our prescribed fire case studies in sagebrush grass. For each task, we present a recommended procedure, a discussion of results obtained from implementing the procedure, and problems encountered.

Task A. Acquisition of fuels data in the field

1. Recommended Procedure

Fuels data should be collected on the data entry forms provided in the publication "BEHAVE: Fire Behavior and Fuel Modeling System--FUEL Subsystem" by Burgan and Rothermel (1984). The first step involves a field reconnaissance to obtain a general impression of the fuels to be modeled. The questions posed in Burgan and Rothermel (1984, page 11) are certainly relevant for consideration, but operationally may not lead to desired results. The following are suggested revisions in the reconnaissance check list:

1. List the fuel components--litter, grass, shrubs, and slash--which are available in significant quantity.

Note: As with this entire checklist, quantitative descriptions are most desirable. Unfortunately, fuel availability may be difficult to estimate in advance of the fire front. Recognizing this difficulty, try to focus on the availability of the fine fuels, i.e. 1-h, live woody, live herbaceous, in making this estimate.

2. Describe the continuity of fuels in terms of the following criteria:

   a. Likely to sustain propagation in the absence of wind (continuous).

   b. Fairly continuous, but will require wind (specify speed) to sustain fire spread.

   c. Discontinuous. You will have to be very careful in interpreting outputs from the fire model.

Note: Though intuitively useful, the notion of fuel continuity is not easily quantified. Further, for some fuelbeds both horizontal and vertical fuel continuity will be important. In the absence of quantitative descriptors, verbal descriptions of the area will be helpful.

3. List the fuel strata most likely to carry the fire, in decreasing order of importance.

Note: The intent here is to force the observer to more critically take note of the fuel complex.

4. Are there large variations in the amount of one or more fuel components? [Note: this statement is probably too subjective to be of much assistance]

5. What proportion of the [available] fuel is in the 1-h, 10-h, 100-h, live herbaceous, and live woody category?

6. How many grass and shrub types must be dealt with?

7. Which bulk density photos best represent the bulk densities of the grasses and shrubs that will carry the fire?

8. Identify the representative locations where you will be able to take measurements for depth of the grasses, shrubs, litter, or slash in the area.

9. Are the fuels sufficiently intermixed that they can be represented by a single model, or do they occur in independent "patches" that may require use of the two-fuel-model concept?

10. What is the most likely direction in which the fire will spread? For prescribed burns, what is the planned ignition pattern, and where will you gather your fire behavior observations?

The main advantage of the suggested revisions to items 1-9 lies in compelling the user to make explicit, pro-active observations, rather than responding to queries which can be easily put aside. Item 10 has been added to help users manage the collection of fire behavior observations.

2. Study Results

Extensive inventory techniques as presented by Brown and others (1982) were only used on one burn (Berry Creek, custom fuel model 62). The extra time and energy needed to complete inventory transects and oven-drying of herbaceous and litter fuels on this one burn did not markedly improve the quality of the initial custom fuel model constructed. This approach was not pursued on other burns, because of the excess time required.

For all burns, fuel depth measurements were made with a yardstick, then bulk depth was visually estimated via the 'pliable sheet' method described in Brown (1982) or using Burgan and Rothermel (1984, figures 5 and 6). Required inputs to NEWMDL, such as percent of area covered by each fuel stratum, and condition of the vegetation, were recorded on NEWMDL inventory forms, and conditions that might affect fire behavior were noted. In addition, photo series provided in Burgan and Rothermel (1984) were used to key out density classes for the grasses and shrubs.

When possible, photographs were taken of the study site to provide perspective for use in building the initial custom fuel model. The photographs were intended to portray the general fuel and slope configuration for the area. Site-specific fuel photographs were also taken, where possible with a standard reference marker of known height. Plant species, camera lens type, and measurements taken on site, such as plant height, were noted on data collection sheets.

3. Problems

We encountered several problems in collecting field data. The problems are inherent to natural fuels in general, and sagebrush-grass in specific, and reflect in part the spatial heterogeneity and plant-species variability of the fuels complex. When using the fuels data collection forms subjectivity was necessary for estimating percent area coverage of one fuel, percent live leaves and twigs, and percent of total load by weight in each timelag category. Further, the procedures for estimating fuelbed depth provide a numeric input for the fuel model, but of unknown accuracy. Even so, the flexibility to modify initial fuel models in TSTMDL generally provides the opportunity to overcome errors in the initial model.

Estimating shrub and grass type and bulk density classes from the photo series was also troublesome, as often none of the shrub and grass types pictured matched the fuels being sampled in the field. Patchiness in the sagebrush-grass cover made extrapolation to average bulk density difficult. We had trouble determining bulk density for the area from the photos, since we knew NEWMDL would reduce our estimates by proportional area coverage.

As evident from later refinements of fuel models in TSTMDL, it is difficult to get fuel measurements that will accurately represent all the areas ignited during the burn. Fuelbed properties change with great frequency, even on a site that appears to be uniform. Although fuels data were collected at the anticipated site of the burn the custom model only reflects fuel properties for a relatively small area.

We doubt whether intensive inventories of fuels would allow creation of more accurate initial fuel models. The traditional fuel sampling techniques provide estimates of biomass or total fuel loadings. Actual fuel availability is determined by the environmental and ignition conditions at the time of burning, but will always be less than total fuels or biomass, especially under the conditions usually prescribed for burning.

Task B. Creation of Initial Fuel Models in NEWMDL

1. Recommended procedure

Based on the data collected on inventory forms, construction of the new site-specific fuel model can proceed as described in the NEWMDL discussion in Burgan and Rothermel (1984, pp 5-24). The procedures are straightforward, although the discussion on multiple-1-hr fuels may be a bit esoteric.

To capture the variability inherent in sagebrush-grass fuels, several fuel models should be constructed. The intent is to construct a sample of initial fuel models, with sufficient variability to realistically represent sagebrush-grass complexes encountered in the field. In addition, NFFL fuel models 1 and 5, and two-fuel model variations on models 1 and 5 should be considered. These different fuel models can be tested and used to parameterize a general fuel model for sagebrush-grass, which is one the main goals of this study. To this end, summary statistics (mean and standard deviation) for the initial fuel model inputs should be computed and tabulated. As a further guide to calibration efforts, similar statistics should be compiled for the fire behavior observations and predictions derived from the various models.

2. Study results

Using NEWMDL, the data collected in the field were entered into initial custom fuel models. These models are summarized in Table 1, along with estimates for SA/V ratios and heat content. Table 1 also includes inputs to NFFL fuel models 1 and 5 for comparison purposes, along with standard deviations for fuel inputs over all models considered.

Fuel models were constructed using the alternative options provided in NEWMDL:

1. Depth and load entered by the user.
2. Depth entered by the user; load estimated by NEWMDL.
3. Load entered by user; depth estimated by NEWMDL.

Thus model 20 was constructed using inventory information on load and depth (option 1) inferred from BLM inventory forms, while models 21 and 22 used options 3 and 2, respectively. Models 50-52 were respectively constructed using options 2, 3, and 1 respectively. Models 60 and 61 relied on option 2, whereas model 62 used option 1. Model 65 was constructed using option 2.

The various fuel models in Table 1 essentially provide a set of sample vectors for representing the sagebrush-grass fuels complex. The intent in computing a sample standard deviation is to essentially mimic the variation encountered in the field for each fuel input. The standard deviation for each vector element

Table 1. Fuel model summaries, by input. Additional fuel model descriptions are given in Appendix A.

	20	21	22	50	51	52	60	61	62	65	5	1	sd
L1	0.19	0.17	0.52	2.38	1.95	1.71	1.61	1.71	2.74	5.75	1	0.74	1.46
L10	0.13	0.11	0.51	1.58	1.3	2.35	1.2	0.83	0.97	1.44	0.5	0	0.67
L100	0.03	0.02	0.1	3.46	2.84	2.01	0.63	0.39	0.45	2.87	0	0	1.27
LH	0.11	0.11	0.01	0	0	0	0.09	0.08	0.29	0	0	0	0.08
LW	0.23	0.21	0.93	2.47	2.03	2.04	0.93	0.92	1.06	4.31	2	0	1.17
SA1	2679	2695	2506	3500	3500	3500	1689	2689	2246	1200	2000	3500	737.
SAH	2800	2800	2800	0	0	0	1300	700	2800	0	0	0	1258
SAW	2300	2300	2300	677	677	677	1300	700	1300	1000	1500	0	723.
*WAF	0.3	0.3	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.4	0.4	0.09
DEPTH	0.4	0.5	0.5	0.8	0.6	0.8	1	0.9	0.9	2.4	2	1	0.58
EXTM	18	18	20	35	35	35	34	34	30	35	20	12	8.4
HEAT	8041	8024	8242	9267	9267	9267	8227	8172	8557	8731	8000	8000	500.

Options used in NEWMDL for each fuel model.

Model	Option
20	Bates Creek, load and depth input
21	Bates Creek, load input, depth estimated
22	Bates Creek, depth input, load estimated
50	Wintersteen, depth input, load estimated
51	Wintersteen, load and depth input
60	Berry Creek, depth input, load estimated
61	Berry Creek, depth input, load estimated
62	Berry Creek, intensive inventory
65	Walden, depth input, load estimated

*WAF = wind adjustment factor

provides both an indication of fuel variability, as well as cut-off points for model calibrations during the refinement process. Thus, although sagebrush-grass fuels exhibit considerable spatial variability, the plus/minus 1 standard deviation (sd) provides a threshold beyond which input modifications must be made with caution.

3. Problems

Surface area to volume ratios and heat content were entered according to judgment about relative sizes of fuel components, time of year, and chemical properties. The cost of obtaining better estimates for heat content and surface area to volume ratios probably is not justified.

We realize that problems may arise from combining actual with derived estimates in Table 1, especially in computing standard summary statistics to describe elements within the fuels complex. However, both inventory and NEWMDL-derived estimates are subject to error, and neither is necessarily more "correct", particularly in terms of fire behavior modeling. Estimates from inventory generally overestimate fuels available for combustion in the flaming front, focusing as they do on total biomass or total fuel present on site. Estimates derived by NEWMDL are subject to error due in part to the manner in which they are apportioned over the area covered. In summary, we felt justified in combining both inventory and NEWMDL-derived estimates to develop an initial set of fuel models, given the exploratory nature of the current effort.

Task C. Obtaining Initial Fire Behavior Predictions with the Fuel Models

1. Recommended procedure

The first step in testing the initial models is to develop fire predictions, depending on the type of information available for the planned burn. When agency prescribed fire plans outline the desired ranges in fuel moisture and windspeed for the area, the DIRECT module of FIRE1 could be used. Alternatively, the SITE subroutine in FIRE1 can be used if prescriptions state specific weather data desired for the day of burn. Often, agencies provide fire behavior predictions based on TI-59 calculations for standard NFFL fuel models.

Fire behavior predictions should be developed for as wide a range of environmental conditions as may be anticipated for the day of burning. Windspeeds in particular may vary considerably over time and space during conduction of a burn. Simulations over wide ranges in environmental conditions will allow users to test the robustness of the fuel model.

Generally, this step should occur prior to collection of fire behavior observations. The main reason is to avoid any potential bias on the part of fire behavior monitors who conceivably might be predisposed toward recording certain measurements if they were involved in generating initial predictions. However, for reasons given below, we do not feel this to be crucial in all situations.

2. Study Results

The fire predictions obtained from initial models are included in Appendix B, using environmental inputs collected for each burn site (see Table 2 below). Where possible, we obtained burning plans and prescriptions in advance of each planned burn and attempted to model expected behavior. Our intent was not to come up with a new fuel model for each burn, but we eventually selected the most representative model for sagebrush-grass fire predictions from among those tested in Appendix B. In certain cases, we experimented with standard fire behavior models, singly and in various combinations (two-fuel-model concept), as well as custom models constructed from site inventories. Multiple fuel models are especially important given the heterogeneity of the sagebrush-grass fuels complex.

3. Problems

Logistical considerations did not always allow us to generate fire behavior predications prior to collection of fuels and fire behavior information on the day of burn. Several burn sites were located as far as 6 hours travel time away from CSU, so we often had to collect fuel and fire behavior information on the day of the burn. We usually had to rely on public agency

burning schedules which only allowed us time to construct the custom fuel model after going into the field to obtain fuels and fire behavior data simultaneously. Often, we developed intuitive feelings for the fuels to be burned, based on burning plans and prescriptions provided by the agencies.

In general, the juxtaposition of data collection tasks did not create problems since the initial custom fuel models were constructed independently of fire behavior data collection. Further, as we found in our analyses, sources for variability were introduced in each of the above tasks, and in aggregate, simply overwhelmed any bias that may have been inherent to not following the recommended sequence.

Task D. Collection of fire behavior observations

1. Recommended procedure

The fire behavior data sheet from "Field Procedures for Verification and Adjustment of Fire Behavior Predictions" by Rothermel and Rinehart (1983) is a useful guide for collecting fire behavior information. Rothermel and Deeming (1980) also gives useful guidelines for focusing on particular aspects of a fire's behavior which can be measured and entered onto the monitoring form. Several standardized, easy to use, portable tools for taking portable measurements may be required, depending on location of observers in relation to the fire front. Techniques and standards for measuring fire behavior are covered in Rothermel and Rinehart (1983) and Zschaechner (1985).

While several observers are taking fire behavior measurements at different points during the burn, at least one person should take weather observations. A standard belt weather kit is useful for recording windspeed, relative humidity, and dry bulb temperatures at systematic intervals during the burns. However, improved, low-cost anenometers currently available may give more reliable estimates for mid-flame windspeeds.

As the burn proceeds, the weather monitor should assume responsibility for calling out the precise time at predetermined time intervals, even if burn monitors have previously synchronized their watches. This allows the burn monitors to focus more of their attention on the fire itself. The time interval for weather collection may vary, depending on the fire's activity. However, we suggest starting out with 5-minute intervals and adjusting as necessary to accommodate the collection of fire data. The main point is to make sure the interval is not so long that weather changes affect successive fire behavior observations.

2. Study Results

Rate of spread and flamelength measurements were the two fire behavior indicators used to test the sagebrush-grass custom fuel models in this study. Fire behavior observations on the burn are given in Table 2, along with the environmental inputs used for driving and testing fire behavior predictions. The average rate of spread observed was 17.8 ch/h (sd = 17.3). Average flame length over all four sagebrush-grass burns was 3 feet (sd = 6.0). Thus the coefficient of variation for ROS was nearly 100%; for FL it was 200%. These estimates indicate the variability of fire spread. More importantly, they indicate the difficulty associated with trying to develop one fuel model to fit all environmental conditions encountered when burning is conducted on multiple sites.

Table 2. Environmental inputs and observed fire behavior

Bates Creek

Obs	Wind	Slope	Temp.	RH	M1	M10	M100	Mwood	Mherb	ROS	FL
1	5	3	79	36	8	11	14	100	75	10	3-6
2	5	3	79	36	8	11	14	100	75	15	4-6
3	0	3	78	30	7	10	13	100	75	2	2-3
4	6	3	77	32	7	10	13	100	75	28	4-6
5	6	3	78	25	6	9	12	100	75	18	2-3
6	6	3	78	25	6	9	12	100	75	8	6
7	6	3	78	25	6	9	12	100	75	23	3
8	6	3	78	25	6	9	12	100	75	23	3
9	6	3	78	25	6	9	12	100	75	23	3
10	0	3	80	31	7	10	13	100	75	6	4-5
11	0	3	80	31	7	10	13	100	75	8	6
12	7	3	80	29	7	10	13	100	75	10	5

Berry Creek (wind at 20')

Obs	Wind	Slope	Temp.	RH	M1	M10	M100	Mwood	Mherb	ROS	FL
1	6	30	66	31	6	9	12	90	65	15	5
2	7	30	66	31	6	9	12	90	65	20	8
3	6	30	64	32	6	9	12	90	65	15	5
4	7	35	61	33	6	9	12	90	65	53	8
5	6	35	61	33	6	9	12	90	65	23	5
6	6	35	63	37	7	10	13	90	65	20	8
7	6	35	64	35	7	10	13	90	65	40	8
8	7	30	63	32	6	9	12	90	65	33	6
9	6	30	63	32	6	9	12	90	65	51	8
10	7	30	63	32	6	9	12	90	65	66	7

Wintersteen

Obs	Wind	Slope	Temp.	RH	M1	M10	M100	Mwood	Mherb	ROS	FL
1	8	50	70	25	5	8	11	90	65	2	6
2	4	50	63	31	6	9	12	90	65	2	4
3	8	50	70	25	5	8	11	90	65	2	4
4	4	50	63	31	6	9	12	90	65	2	3

Walden (wind at 20')

Obs	Wind	Slope	Temp.	RH	M1	M10	M100	Mwood	Mherb	ROS	FL
1	0	0	69	33	8	11	14	75	65	1	2-5
2	0	0	65	31	6	9	12	75	65	3	6-20
3	20	0	72	28	6	9	12	75	65	12	9-15
4	23	0	65	31	9	12	15	75	65	1	6-15
5	12	0	63	32	8	11	14	75	65	1	14
6	10	0	65	31	7	10	13	75	65	1	2-3
7	8	0	64	31	7	10	13	75	65	3	10
8	23	0	72	28	6	9	12	75	65	40	NA
9	33	0	66	35	6	9	12	75	65	50	NA

NA = unavailable

3. Problems

Fire behavior monitoring is not a straightforward procedure. The problems relate to the variability in a fire's behavior over space and time. Spatial variability in fuel and environmental data collection at the time of fire behavior observation also contribute to data collection problems. A fire's front may, in fact, be too large of an area for data collection, even in uniform fuels. Instead, small triangular (Simard and others 1984) or hexagonal (Smith and others, in prep.) fixed plots may be more desirable for both fuel and fire behavior observation.

Due to burn objectives, weather conditions, and firing patterns a representative steady-state line fire was not observed on all of the burns. Several burns (Bates Creek and Martin-Marietta) were conducted under marginal burning conditions. Several were vigorous fall burns (Walden, Berry Creek and Wintersteen) conducted primarily as backing fires.

It is important to accurately measure ROS and flamelength to minimize the error between the observed and predicted observations. Error enters into the observations because of subjectivity in differing perceptions of distance and height, and lack of adequate portable measuring tools. The importance of these errors cannot be overlooked, since fire behavior observations are crucial for calibrating and refining the fuel model.

Task E. Analysis of Observed vs. Predicted Fire Behavior to select one Custom Fuel Model

1. Recommended Procedure

The predicted ROS and FL for each site model should be recorded and compared to the actual observations. In addition, all observations should be pooled together and run through each initial fuel model. The fuel model producing the best predictions should be be identified and selected for future calibration and refinement efforts.

Rothermel and Rinehart (1983) describe methods for plotting and analyzing observations versus predictions for rate of spread and flame length. Graphical displays of observed vs predicted values are useful for developing a feel for fuel model performance, and may provide additional insight into options for model calibration, as well as suggesting possible data transformations to improve "fit."

Further insights are possible by use of regression analysis of predicted versus observed fire behavior. Several programs exist for this purpose, including those available in mainframe or microcomputer environments, as well as options available on the HP 71B or TI-59 calculators. Rothermel and Rinehart (1983) also describe methods for doing this with a transparent ruler or straightedge.

Based on graphical or statistical analyses, a "best" fuel model can be selected. This may in fact be one of the initial fuel models, or a variant of these which provides good agreement between observations and predictions. The purpose of this initial selection is to provide a starting point for refinements and calibrations with TSTMDL. This initial model may, in fact, be one of the standard FBO models if it provides reasonable predictions.

2. Study Results

We graphed and regressed predicted versus observed rate of spread and flame length, for each fuel model, using MINITAB. The fit of predictions to observations was examined for each individual fuel model and case study fire. Then all predictions were regressed against observations using each fuel model (Table 3). Fits were generally poor with untransformed data, although ln-ln (natural log) transformations considerably improved rate of spread regressions (Table 3).

Table 3. R^2 values for fuel model predictions for observed fire rate of spread and flame length. Regressions attempted with untransformed data are denoted as 'Reg.', while 'Ln' indicates natural log transformations for predictions and observations.

FM No		20	21	22	50	51	52	60	61	62	65	5	1	5+1
ROS	Reg.	64.2	61.7	75	47.9	52.2	49.9	71.3	47.2	40.8	57.3	52.8	51.3	58.8
		63.1	60.5	74.2	46.3	50.7	48.4	70.4	45.6	39	56	51.4	49.8	57.5
	Ln	86.2	77.3	66.2	79.6	81.7	80.5	79.5	75.3	76.5	74.4	82.7	82.8	83.9
		85.8	76.6	65.1	79	81.1	79.9	78.9	74.5	75.8	73.7	82.2	82.2	83.4
FL	Reg.	0.9	1.3	1.3	0.2	0	0.1	0	0.2	0	0	0.8	0.1	0
		0	0	0	0	0	0	0	0	0	0	0	0	0
	Ln	1.9	1.8	3.6	2.3	1.2	1.9	1.2	3	1.2	2	3.4	0.4	1.2
		0	0	0.5	0	0	0	0	0	0	0	3	0	0

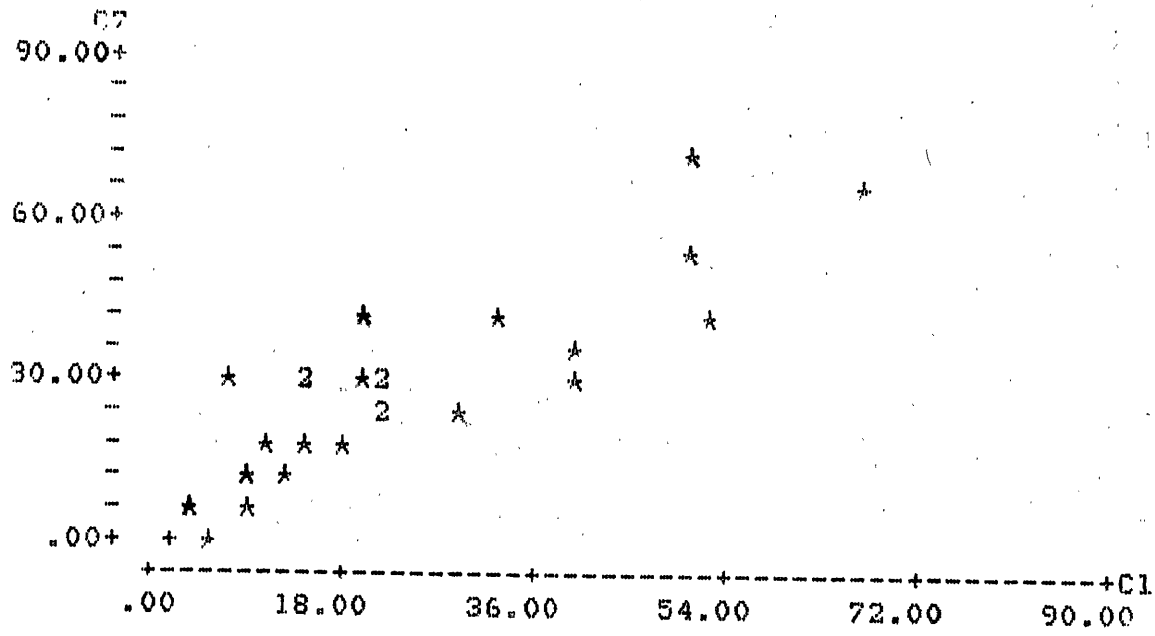
The custom models tended to underpredict both ROS and flame length, with flame length underpredicted to a greater degree. We speculate that underpredictions are more likely on prescribed fires, especially those conducted at the lower end of the prescription window, especially if weighted moistures are near the moisture of extinction. Other possible reasons include consistent overestimation of flame length in the field or underestimation of environmental inputs. We chose to examine fuel parameters that have the greatest effect on rate of spread and flamelength.

The two-fuel model combination of NFFL 5 (80%) and NFFL 1 (20%) generally overpredicted both rate ROS and flamelength. We did not experiment further with the two-fuel model concept, choosing instead to focus our calibrations on the model which gave the best overall fit based on R^2.

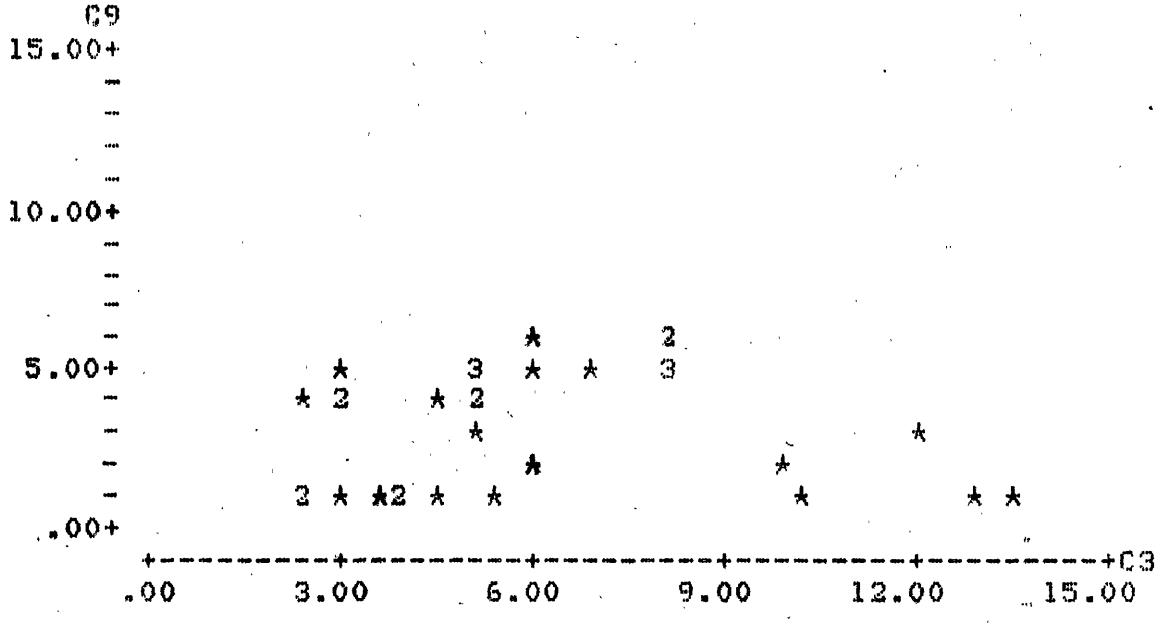
After examination of regression analyses, fuel model 20 was selected as the initial fuel model. Figure 1 shows comparisons between predictions vs observations for ROS and FL using fuel model 20. All subsequent refinements were based on the performance of fuel model 20, as represented in the technical graphics section of TSTMDL. As an alternative, we could have selected the two-fuel model for calibration, which performed almost as well as fuel model 20, but which tended to overpredict ROS and FL. In either case, the algorithm presented below could be used to adjust the initial model as desired.

Figure 1. Predictions (y axis) versus observations for ROS and FL, using fuel model 20.

ROS



FL



3. Problems

Graphical and regression analysis procedures can be time-consuming, particularly for a large number of fuel models being tested. However, considerable insight is gained by plotting observed versus predicted fire behavior measurements and conducting the regression analyses. Alternatively, plots may be drafted by hand, although the most superior fuel model may not be so readily apparent in the absence of standard regression statistics.

Another problem arose when weather measurements were not collected precisely at the moment of fire behavior data collection. In these instances, we had to assume the fire weather remained constant between successive fire behavior observations.

Task F. Refinements and Calibrations using TSTMDL

1. Recommended procedure

The first required step is to determine if the model refinements are necessary at all. In the absence of discrepancies between observations and predictions, or if existing differences are deemed acceptable for intended uses, then no further calibration will be necessary.

Assuming that improvements are needed, the user should verbalize these as concisely as possible. For example, suppose the fuel model consistently overpredicts spread rates or flame length. The user must then decide if improvements in ROS or FL (or both) are more desirable. Further, a determination must be made as to relative changes desired in ROS and FL estimates, as changes in specific fuel inputs will evoke differential output responses. Thus, the user should determine whether greater relative changes are needed in ROS or in FL. The uses of TSTMDL outputs may vary depending on the these determinations.

There are many options for calibrating the fuel model. Rothermel and Rinehart (1983) describe an approach based on developing corrections factors to model outputs. Their methods involve graphical and regression analyses, and are useful for developing correction factors for rate of spread, flame length, and moisture of extinction.

The TSTMDL system facilitates model corrections to fuel and environmental inputs for ROS and FL. Considerations for modifying inputs are given in Burgan and Rothermel (1983, pp 48-49). In summary the following inputs are especially important:

a. loading estimates, by category, particularly in the 1-hr dead (L1), live herbaceous (LH), and live woody (LW) categories; increases generally increase ROS and FL so long as the packing ratio is less than or equal to optimal. Increases in the 10-hr (L10) and 100-hr (L100) classes can decrease spread rates, but effects on flame length may vary.

b. surface area volume estimates, particularly in the 1-hr dead (SA1), live herbaceous (SAH), and live woody (SAL) classes.

Increases in these SA/V ratios tend to increase ROS, unless the fuels are too-tightly packed. In the latter instance, ROS and FL may decrease.

c. depth estimate (DEPTH). Increases to DEPTH generally increase ROS; no generalizations can be made about the impact on FL.

d. environmental estimates, particularly 1-hr moisture content (M1), midflame windspeed (WIND), and slope (SLOPE). Increases to fine fuel moisture dampen ROS and FL; wind and slope increases both ROS and FL, with relative increases in wind having a greater proportional impact than slope.

e. moisture of extinction (EXTM), as computed internally for each fuel model. Increases to EXTM will allow the fire to spread at higher moistures; intensities will correspondingly increase, thus promoting higher ROS and FL.

f. heat content (H), particularly for fine-tuning model outputs. Again, H directly influences intensity, ROS, and FL.

Burgan and Rothermel (1984) mention the importance of using TSTMDL to plot changes in ROS, FL, and ROS/FL associated with the the above inputs. However, the use and interpretation of these three important graphical displays is not detailed.

RECOMMENDED ALGORITHM

The procedures recommended below rely heavily on the use of these three displays to determine the appropriate input changes for bringing about the desired changes in relative magnitude and direction (increase vs decrease) in fire behavior predictions. Sequentially, the recommended iterative steps to be followed are:

1. Examine the discrepancies between observations and predictions. If no discrepancies exist or you are satisfied with the fuel model predictions STOP.

2. Classify the corrections generally being sought. Major possibilities include:

   a. The fuel model consistently gives good predictions for ROS but (over)underpredicts FL. Solution: Select fuel input change that (decreases) increases FL while holding ROS relatively constant. Go to 4.

   b. The fuel model consistently gives good predictions for FL but (over)underpredicts ROS. Solution: Select fuel input change that (decreases) increases ROS while holding FL relatively constant. Go to 4.

   c. The fuel model consistently overpredicts ROS but underpredicts FL. Solution: Select fuel input change that decreases ROS while increasing FL. Go to 4.

   d. The fuel model consistently underpredicts ROS but overpredicts FL. Solution: Select fuel input change that increases ROS and decreases FL. Go to 4.

e. The fuel model consistently overpredicts or underpredicts both ROS and FL. Solution: increase fuel and environmental inputs that uniformly affect both ROS and FL. Go to 3.

f. The fuel model consistently overpredicts or underpredicts both ROS and FL, although in varying relative magnitudes. Solution: Select and change fuel input that has the desired relative impact (ie greater impact on ROS or FL, as required). Go to 4.

g. The fuel model gives inconsistent predictions for either ROS or FL. Additional fuel models and/or fire behavior observations may need to be collected, after which the fuel model can be re-initialized, prior to returning to 1.

3. Several options exist. Adjustments to windspeed, fuel moistures, moisture of extinction, heat content, or new fuel model correction factor (as explained in Rothermel and Rinehart (1983) can be used to adjust consistent over- or underprediction. Go to 1.

4. Tabulate the ranges in fuel inputs to which model ROS, flamelength, and ROS/FL are insensitive and sensitive. This table is compiled by running TSTMDL graphics and noting the slopes and inflection points in ROS, FL, and ROS/FL functions as individual fuel inputs change. Based on this table, a fuel input to be modified and "reasonable" calibration ranges may be identified.

IMPORTANT: The key here is to identify the resultant changes in ROS or FL due to marginal increments (or decrements) in influential fuel inputs, based on the slope of the ROS/FL graph and examination of the ROS and FL changes. Comparisons between output changes associated with the various inputs should reveal which are feasible candidates for change. However, the desired responses may only occur along discrete ranges of input changes. It is further important to realize that the ROS/FL could increase in response to input changes, even though both ROS and FL are decreasing, if ROS is decreasing at a slower rate than FL. Similarly, ROS and FL increases could result in a negatively-sloped ROS/FL graph, if input changes caused FL to increase at a faster rate than ROS. Thus the user should examine the effect of the input changes by referencing the ROS/FL, ROS and FL graphs, and should then accordingly evaluate the new "fit" of observations to predictions using TSTMDL in combination with graphical or regression analysis. The user should then return to step 1.

As a practical guideline, users should probably place some upper limit on the changes to be imposed in a single fuel input (say, +/- 1 sd) before returning to step 1. Changes outside this boundary should be carefully evaluated in terms of their reasonableness. Users should also be aware that fuel inputs should initially be changed one at a time; that changes in one fuel input may have effects on the influence of other fuel inputs.

2. Study Results

On the basis of regression and graphical analyses, we determined that Fuel Model 20 underpredicted both ROS and FL, but FL by a greater relative magnitude (situation 2f in the above algorithm). Multiple correlation coefficients for ROS were 64.2 (86.2 for ln-ln regression); for FL we only achieved r-squares of .9 and 1.9. Thus our calibration attempts focused on increasing both, with greater relative emphasis on FL increases.

TSTMDL graphs for ROS/FL, ROS, and FL as functions of fuel inputs were examined for Fuel Model 20, under representative environmental conditions[2]. On each graph, the Model 20 input value was noted, along with the slope of the ROS/FL graph and anticipated changes in ROS and FL. In so doing, we were also able to compare the relative importance of marginal changes in fuel inputs, and were able to identify which fuel inputs could be removed from further consideration. Example graphs for input L1 are presented in Figures 2-4. Similar graphs were constructed in TSTMDL for inputs SA1, SAH, SAW, L10, L100, LH, LW, DEPTH, and EXTM. Inflection points and sensitivity of graphs to variations in fuel inputs were tabulated (Appendix C) and excerpted below (Table 4) for illustration purposes.

Table 4. ROS/FL sensitivity to fuel input changes, fuel model 20. The direction of the inequality indicates whether the output is increasing (<) or decreasing (>) over the fuel input range being considered.

ROS/FL Input	Model 20 Value	Sensitivity Range
L1	(.19 T/A)	1.9>ROS/FL>1.1 for .001<L1<.02 1.1<ROS/FL<6.5 for .02<L1<.19 6.5>ROS/FL>4 for .19<L1<5.8 ROS/FL = 4 for 5.8<L1<14 4<ROS/FL<6.3 for 14<L1<30
L10	(.13 T/A)	7>ROS/FL>2 for .001<L10<5 2>ROS/FL>.8 for 5<L10<30
LH	(.11 T/A)	6.6>ROS/FL>2.2 for .001<LH<.83 2.2>ROS/FL>.3 for .83<LH<18 ROS/FL = .8 for 18<LH<30
LW	(.23 T/A)	6.2>ROS/FL>.4 for .001<LW<5 ROS/FL = .4 for 5<LW<30

[2]The environmental inputs used were M1 = 6%, M10 = 9 %, M100 = 12 %, MHERB = 65%, MWOOD = 90%, WIND = 5, and SLOPE = 35.

Figure 2. ROS/FL sensitivity to changes in L1, fuel model 20. Negative slope indicates regions where FL increases faster (or decreases at a slower rate) than ROS in response to increases in L1.

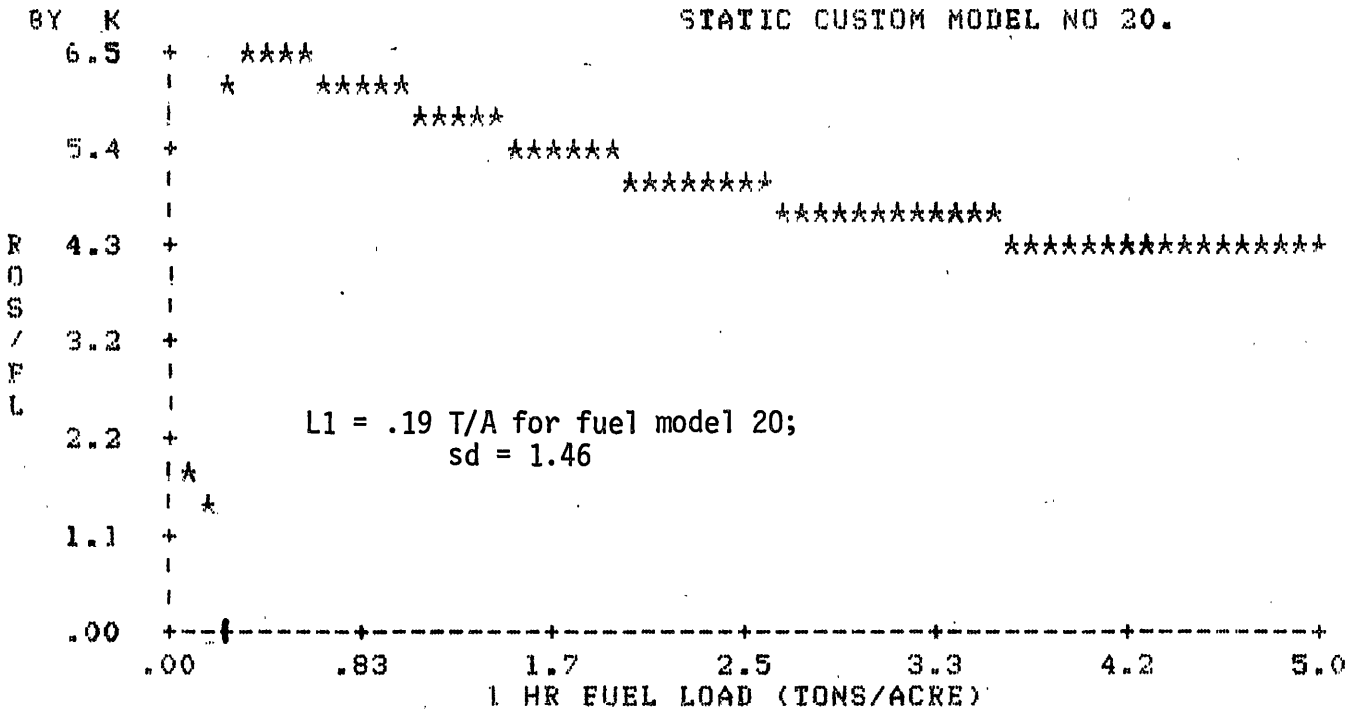


Figure 3. ROS sensitivity to changes in L1, fuel model 20. (The environmental inputs used were M1 = 6%, M10 = 9 %, M100 = 12 %, MHERB = 65%, MWOOD = 90%, WIND = 5 mi/h, and SLOPE = 35%)

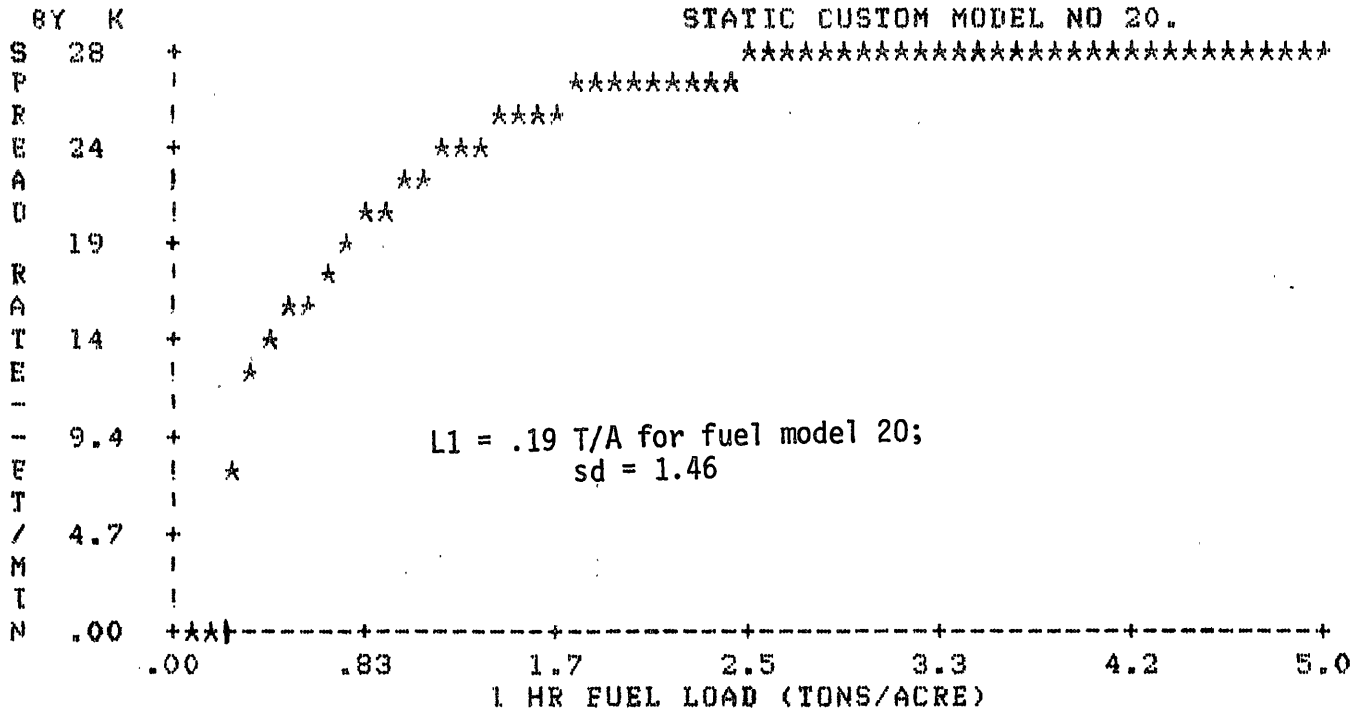


Figure 4. FL sensitivity to changes in L1, fuel model 20. (The environmental inputs used were M1 = 6%, M10 = 9 %, M100 = 12 %, MHERB = 65%, MWOOD = 90%, WIND = 5 mi/hr, and SLOPE = 35%)

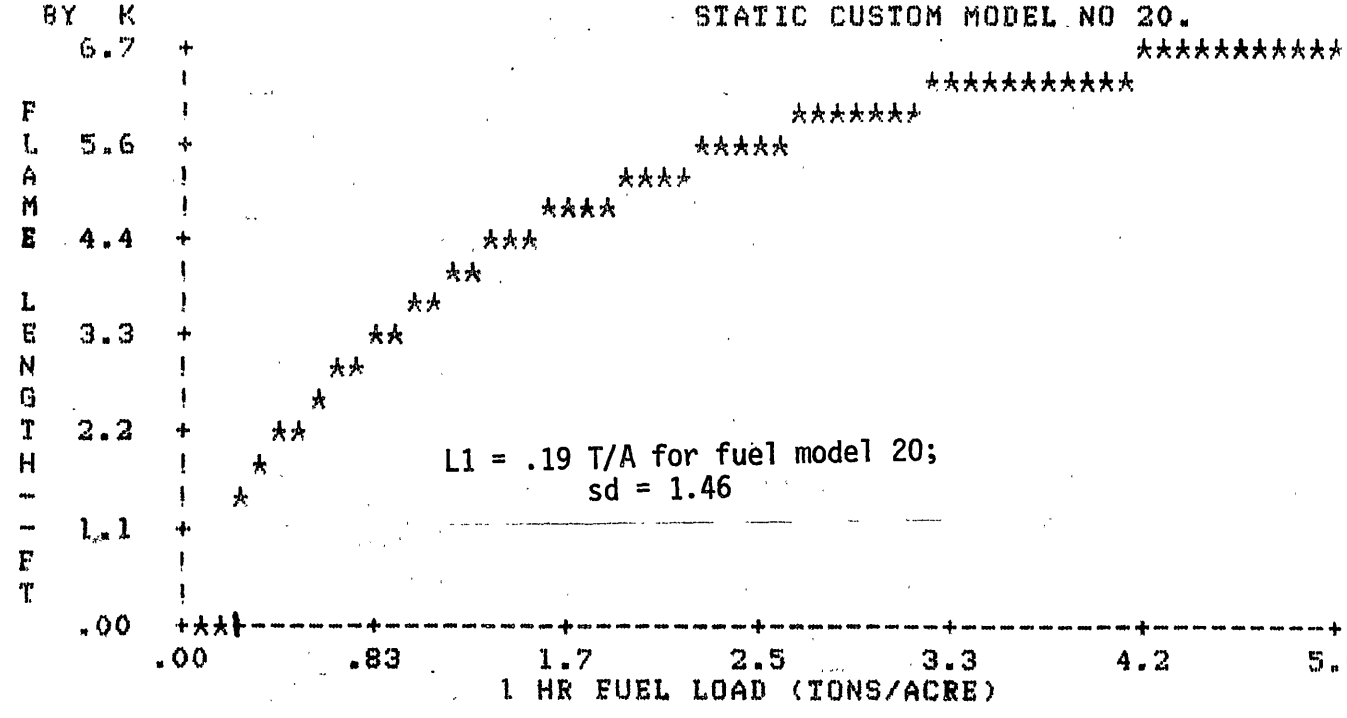


Table 4 indicates that ROS/FL will decrease over certain ranges in fuel inputs, for example for .19<L1<5.8 T/A and .001<LW<5 T/A. That is, the change in FL is greater than the change in ROS in these ranges for L1 and LW. However, to verify that L1 and LW increases are indeed going to result in higher relative increases to FL (as opposed to ROS), we must also check how ROS and FL individually change over the same ranges. In fact, Table 5 shows that FL increases over the L1 range, but actually decreases over the LW range. The reason for this is that the slope of FL is less negative than the slope for ROS over the LW range. Thus increases in L1 are more likely to bring about the desired relative increases to FL, at least within the input ranges specified. Further, this example points out the importance of not restricting attention solely to ROS/FL, but also verifying that the desired changes in ROS and FL actually occur.

Table 5. ROS and FL sensitivity to selected fuel input changes, fuel model 20. The direction of the inequality indicates whether the output is increasing (<) or decreasing (>) over the fuel input range being considered.

Input	ROS (ft/min) Sensitivity Range	FL (ft) Sensitivity Range
L1	0<ROS<28 for .001<L1<5 28>ROS>11 for 5<L1<30	0<FL<6.7 for .001<L1<5 6.7>FL>1.6 for 5<L1<30
L10	10>ROS>5.4 for .001<L10<1 ROS = 5.4 for 1<L10<4 5.4<ROS<5.7 for 4<L10<7.1 5.7>ROS>1 for 7.1<L10<30	1.4<FL<3.6 for .001<L10<8.3 FL = 3.6 for 8.3<L10<10.3 3.6>FL>1.8 for 10.3<L10<30
LH	8.7<ROS<10 for .001<LH<.14 10>ROS>.1 for .14<LH<.28 .1>ROS>0 for .29<LH<30	1.3<FL<1.6 for .001<LH<.14 1.6>FL>.26 for .14<LH<.28 .26>FL>.1 for .28<LH<5 .1>FL>0 for 5<LH<30
LW	8.7>ROS>0 for .001<LW<1.6 ROS = 0 for 1.6<LW<30	1.2>FL>.1 for.001<LW<5 .1>FL>0 for 5<LW<30

Based on Tables 4 and 5, increases to L1 were identified as bringing about the desired increase in FL and ROS, with greater proportional changes in FL. The initial increase to L1 attempted was to 1.65 T/A, representing an increase of + 1 sd. This made the model predict ROS better but FL predictions still were too low (though better than without the change). The R-square for ROS improved to .83 but FL was .02. We returned to TSTMDL and ran the ROS/FL and FL graphs, and learned that further increases in L1 would continue to have greater influence on FL than ROS. We also noted that increases in LH and L10 would produce this

same effect, although increases to LH beyond .14 T/A would begin to decrease FL. So we fixed LH at .14 T/A and ran two additional models. The first increased both L1 and L10 by +1 sd. The second increased both by +2 sd. Changes to the fuel model were entered in the "Fuel" section of TSTMDL, and predictions for the new model were made using the same environmental conditions as measured during the test burns. Observations were compared to predictions using MINITAB.

The R-squared values for the 1 sd model were: ROS, 81.9 (for the ln-ln regression, and FL, 2.3. For the 2 sd model, ROS was 82 and FL was 3.1. Further improvements in FL could have been achieved (i.e. by increasing L1 as high as 5 T/A and L10 to 8 T/A), but we didn't feel justified in increasing fuel inputs so far beyond + 2 standard deviations. Examination of the data suggested that the low r-squares for FL resulted in part from wide ranges in observations (6-20') associated with the same environmental conditions on one burn.

3. Problems

The approach taken in this study focuses primarily on manipulation of fuel inputs to attain greater conformance of predictions to observations. We directed our focus on those inputs which reasonably could be expected to result in greater agreement between observations and predictions by employing the above algorithm. Potential deviations due to fire or environmental measurement errors could not be assessed.

One of the problems with this approach is that fuel input changes within the +/- 1 sd interval may be insufficient to induce the desired impact on ROS or FL. Considerable judgment will be required to determine if greater deviation is justifiable, or whether more than one fuel input should be changed simultaneously.

Several problems arose during our sensitivity analysis. In some cases the change in fire behavior would be very dramatic within a very small change in the fuel factor. When the +/- 1 sd interval includes this break point (essentially a step function) eg, for SAH and SAW, the user should take care in assessing the changes in fire behavior in the neighborhood of the break point. The effects of fuel input changes in the neighborhood of such break points are more easily examined if the desired range in the independent variable is reduced in TSTMDL graphics.

In some cases, nearly identical environmental parameters produced similar observed fire behavior. In other cases, similar environments resulted in quite different fire behavior. There were also a few observations that showed dramatic increase in ROS without a proportional increase in FL for the same environmental parameters. We hypothesized that the fire may have changed fuel type at this point, perhaps where the fire was being carried

primarily by grasses, and not the predominant shrubs. Outlying points defy prediction, no matter how many changes are made to the model.

The ultimate test of "reasonableness" is provided by the conformance between observations and predictions. However, this agreement should not be achieved by sacrifices in the integrity of fuel estimates. In other words, throughout the refinement process, the changes to fuel estimates used should be continually evaluated in terms of their sensibility. Also, given the flexibility provided in TSTMDL, users should restrict calibration efforts to changes in fuel inputs, while keeping mindful that environmental inputs or observer error may also be responsible for observed-predicted discrepancies. This is not to neglect the possibility of discrepancies due to improper environmental measurement (however likely); but, difficulties arise while calibrating both fuel and environmental inputs, especially given the additional uncertainty presented by fire measurement errors.

Further, users should understand that they might not find one single model which uniformly represents the sagebrush-grass complex. Additional models might be necessary for different areas; a separate models might be necessary for flame length as opposed to rate of spread. Much will depend on the objective of the modeling effort, i.e., greater emphasis might be placed on flame length (and reaction intensity) estimates for a burn emphasizing fire effects or control difficulties; by contrast, spread rates may be of greater concern for estimating length of line to be constructed or indicating potential perimeter growth.

The process described above essentially minimizes the importance of initial fuel model specification, since emphasis is placed on refinement and calibration to fire behavior observations. This does not negate the importance of precise fuel inventory, but does reduce the accuracy required to proceed. The computer generated loading figures from user input of fuel depth in NEWMDL are probably quite acceptable within this context.

Finally, users do not need to use regression analysis, nor rely solely on the magnitude of R-square for making decisions about calibration. We used this indicator here, but less rigorous standards are entirely acceptable for field application.

CONCLUSIONS

Accurate initial fuel data is important to obtain a representative first cut model that will provide a good base for honing the model. Construction of several models also allow computation of a sample standard deviation which provides a convenient (though not rigorous) cut-off for calibration efforts. However, the crux of the modeling effort occurs in the refinement phase (Task F). Here the experience and judgment of the user must be integrated with familiarity with the fire model and the relationships between model inputs and outputs embodied therein; also, the user must be able to concisely identify the types of refinements desired, the conformance of the model to field conditions, and when to stop the refinement process. The technical graphics section of TSTMDL provides great assistance in identifying important fuel inputs for consideration, but will not make such judgments for the user.

Prioritizing fuel parameters to be changed will be a subjective process, unique to each situation. Identification of the most sensitive fuel inputs for fire behavior (via the technical graphics section of TSTMDL) provides a starting point for fuel model modification. Streamlining the actual modification process would be helpful--perhaps by developing a driver program that prompts for changes in fuel parameters and makes runs using the graphics portions of TSTMDL to alleviate the repetitive, and time-consuming, user prompts required on single runs. Alternatively, a separate program that identified input ranges associated with desired ROS, FL, and ROS/FL changes might also be helpful. Print-out of intermediate values of fire behavior predictions, such as reaction efficiency, may also prove helpful in calibrating fuel models. Thus, initial fuel inputs could be modified to more accurately reflect the anticipated mass loss in the fire's front. Post-burn examinations may provide indications of whether combustion efficiency is consistent with fuel reductions observed in the field.

Fire behavior and environmental data collection should be as accurate as possible, with as many observation points as possible paired with representative weather data. The potential for error may be much greater in the behavior and environment measurements than in assembly and refinement of the fuel model. With time, methods for data collection should improve; however, the ephemeral qualities of fire and environment will continue to pose problems for modelers. In particular, flame length and wind measurement procedures will need improvement. Additionally, the possibility does exist that flame length predictions appended to Rothermel's (1972) spread model may need reexamination.

Our inability to markedly improve the accuracy of flame length predictions with reasonable fuel input changes may suggest the need for additional fireline intensity research. In particular, relationships between rate of spread, fireline intensity, and flame length may require further development in sagebrush-grass fuels. Also the relationship between predictions and observations is probably not linear.

In fact, separate models may be required for ROS and FL, even if the fuels appear to be homogeneous. There are several precedents for using different models to predict various aspects of the behavior on the same fire. Barney and others (1978) used different fuel models for heading, backing, and flanking fires in interior Alaska. Although they used NFDRS fuel models, their approach could be appropriate when using standard fire behavior models as well. Norum (1982) developed different models for modeling ROS, FL, and other fire properties in Alaska black spruce (Picea mariana) forests. Salazar and Bevins (1984) suggest different models may be required for different ages of untreated conifer slash. Similarly, the heterogeneity of sagebrush-grass fuels may indicate the need for "spatially-dynamic" fuel models, perhaps best represented by ranges in fuel inputs in contrast to single-valued fuel models in use today. Development of these models require sophistication and expertise, but enhanced techniques are currently available through NEWMDL and TSTMDL. Many potential applications exist if users are willing and able to invest the time and patience necessary to improve fire behavior predictions.

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APPENDIX A

Initial Models Constructed Using NEWMDL

BATES CREEK BURN
****

CUSTOM FUEL MODELS DEVELOPED IN NEWMDL:

Model 20--grass,load and depth
shrub,loadby category
Model 21--grass,load only,depth estimated
shrub, " " " "
Model 22--grass,depth only,load estimated
shrub, " " " "

General Site Description:

Bates Creek prescribed burn took place on 9/18 near Casper, Wyoming. The fuel type was sagebrush with a 60% cover and fine grass (Idaho Fescue, Wheatgrass) with an 85% cover. A high proportion of grass was still live (65%) because of an unusually wet summer. Slope was less than 10% for all observations. Fuels were exposed to the wind. There was incomplete weather data for the burn site, but there was no rain the week before the burn; a storm was approaching. The weather condition the day before the burn was mild. There was no cloud cover and all weather observations were taken at the burn site.

The objective of the burn was to eliminate sagebrush in drainages to facilitate grass growth for forage of antelope and cattle. The firing method was a head fire, done with drip torches.

Fuel Model 20 PARAMETERS
****

Load (T/AC)		S/V Ratios		Other	
1 hr	.19	1 hr	2679.	depth	.4
10 hr	.13	live herb	2800.	heat content	8041.
100 hr	.03	live woody	2300.	ext moisture	18.
live herb	.11				
live woody	.23	wind adjustment factor:		.3	

FUEL MODEL 21 PARAMETERS
****

Load (T/AC)		S/V ratios		Other	
1 hr	.17	1 hr	2695.	depth	.5
10 hr	.11	live herb	2800.	heat content	8024.
100 hr	.02	live woody	2300.	ext moisture	18.
live herb	.11	wind adjustment factor:		.3	
live woody	.21				

FUEL MODEL 22 PARAMETERS
****

Load (T/AC)		S/V Ratios		Other	
1 hr	.52	1 hr	2506.	depth	.5
10 hr	.51	live herb	2800.	heat content	8243.
100 hr	.10	live woody	2300.	ext moisture	20.
live herb	.01				
live woody	.93	wind adjustment factor:		.4	

SITE ENVIRONMENTAL PARAMETERS
****

Observ. No.	Time	Aspect	Hand-held Anemometer Windspeed	Dir. of wind Vector	Dry Bulb (F)	RH	Dir. of ROS Calc. (0-360)
1	1240	sw	5	0	79	36	0
2	1242	sw	--	0	--	--	0
3	1244	sw	0	0	78	30	0
4	1250	sw	6	0	77	32	45
5	1253	sw	6	0	78	25	45
6	1241	sw	--	0	--	--	0
7	1249	sw	--	0	--	--	45
8	1241	sw	--	0	--	--	0
9	1249	sw	--	0	--	--	45
10	1310	ne	0	225	80	31	315
11	1313	ne	--	225	--	--	315
12	1315	ne	7	225	80	29	315

FIRE BEHAVIOR OBSERVATIONS
****

Observation No.	ROS (CH/HR)	Flame length (Feet)
1	9	3-6
2	13.6	4-6
3	1.8	2-3
4	25.3	4-6
5	16.4	2-3
6	6.8	6
7	20.5	3
8	20.5	3
9	20.5	3
10	5.2	4-5
11	7.5	6
12	8.7	5

MARTIN-MARIETTA BURN

Custom Fuel Models from NEWMDL

Model 30--depth data entered only,load estimated

Components:
Grass--medium/rough fescue,depth 6 inches, 80% current live, 30% coverage.
Litter--from hardwoods, normal compactness, .1 foot depth, 10% 1 hrtl, 90% 100 hrtl, 60% area coverage.
Oakbrush--medium stems, thin leaves; 4 feet depth, 30% 1 hrtl, no 100 hrtl, 70% live leaves and twigs, 60% coverage.

Model 31--depth data entered only, load estimated

Components:
Grass--same as model 30
Litter-- " " " "
Mountain Mahogany--fine stems, thin leaves; 2.5 foot depth, 10% 1hrtl, 90% live leaves and twigs, 25% area coverage, no 100 hrtl.

GENERAL SITE PARAMETERS

This burn occurred in Colorado on October 11. A prescription for the burn was based on NFFL fuel models 1 (grass); 6 (oakbrush); and 9 (mountain mahogany). The burn did not achieve its objective of burning off brush for Bighorn sheep habitat improvement even though burning was done within prescription parameters. There was no cloud cover; fuels were exposed to the wind. Aspect was south; slope was 50 %. The RH was corrected for the fire elevation. There was incomplete weather data for the week prior to the burn, but a storm was approaching. Firing method was strip head firing with drip torches.

FUEL MODEL PARAMETERS

Fuel Model 30

Load (T/AC)		S/V Ratios		Other	
1 hr	1.22	1 hr	2086.	depth	1.58
10 hr	.00	live herb	2300.	heat content	8145.
100 hr	1.47	live woody	1800.	ext moisture	17.
live herb	.04				
live woody	2.44	Wind adjustment factor:		.5	

Fuel Model 31

Load (T/AC)		S/V Ratios		Other	
1 hr	.23	1 hr	2385.	depth	.22
10 hr	.00	live herb	2300.	heat content	8133.
100 hr	1.42	live woody	1800.	ext moisture	14.
live herb	.04				
live woody	.56	Wind adjustment factor:	.3		

SITE INPUT

Observ. No.	Time	Hand-held Anemometer Windspeed	Dir. of Wind Vector	Dry Bulb (F)	RH	Dir. of ROS Calc.
1	1227	4-5	0	77	20	max
2	1240	9-10	0	79	29	max
3	1255	9	0	80	30	max
4	1305	10-11	0	76	31	max
5	1325	3-4	0	78	26	max
6	1413	4	90	77	25	max

Fire Behavior Observations

Erratic but low-key fire behavior made taking ROS and flamelength measurements impossible. Brush was consumed when wind gusts hit 15-20 mph, otherwise the fire burned only the understory of grass and the tops of the brush remained unburned.

WINTERSTEEN BURN
****

Custom Fuel Models from NEWMDL:

Model 50--depth data entered only, load calculated
Model 51--load data entered only, depth calculated
Model 52--all inputs provided by user

Fuels: All shrub: Big Sagebrush, Bitterbrush, Squaw Currant, Thimbleberry, Wild Rose, Mountain Ninebark, Juniper, Rocky Mountain Maple, Waxflower.

GENERAL SITE PARAMETERS
****

The shrub plots of this Poudre Canyon burn project were ignited with a backing fire on September 29. The slope was varying from none on lower valley bottoms to 45% on mid- and upper slopes. Aspect was s-se.

FUEL MODEL PARAMETERS
****

Model 50

Load (T/AC)		S/V Ratios		Other	
1 hr	2.38	1 hr	3500.	depth	.80
10 hr	1.58	live herb	0.	heat content	9267.
100 hr	3.46	live woody	677.	ext moisture	35.
live herb	.00				
live woody	2.47	Wind adjustment factor:		.5	

Model 51

Load (T/AC)		S/V Ratios		Other	
1 hr	1.95	1 hr	3500.	depth	.60
10 hr	1.30	live herb	0.	heat content	9267.
100 hr	2.84	live woody	677.	ext moisture	35.
live herb	.00				
live woody	2.03	Wind adjustment factor:		.5	

Model 52

Load (T/AC)		S/V Ratios		Other	
1 hr	1.71	1 hr	3500.	depth	.79
10 hr	2.35	live herb	0.	heat content	9267.
100 hr	2.01	live woody	677.	ext moisture	35.
live herb	.00				
live woody	2.04	Wind adjustment factor:		.5	

	PROPOSED PRESCRIPTION	ACTUAL CONDITIONS
Time of day	1000-1400	1200-1700
10 hrtl	7-12%	8%
Dry Bulb	45-80 (F)	63-70 (F)
RH	12-35%	25-31%
Wind	3-10 mph	4-8 mph
Wind Direction	s-se	e-ne
State of Weather	Clear to partly cloudy with no major fronts approaching; less than .2 inches precip. the last 48 hours.	Scattered clouds at middle and upper elevations

FIRE BEHAVIOR OBSERVATIONS

ROS (ch/hr)	Flamelength (ft)
1.8	5.5
1.6	4.0
2.1	4.0
1.4	3.0

BERRY CREEK BURN
****

Custom Fuel Models created in NEWMDL:

Model 60--sage,grass,litter,depth only,load estimated
Model 61--sage,grass,litter, " " " "
Model 62--sage,grass,litter,intensive inventory

Fuels: sagebrush--2 foot depth,25% 1hrtl, 5% 100 hrtl, 60% live leaves and twigs, 60% area cover.
grass--medium coarse like rough fescue, 1 ft. depth, 10% live, 40% area coverage.

GENERAL SITE OBSERVATIONS
****

The Berry Creek prescribed burn took place in Colorado. Weather observations were taken within 1000 feet elevation of the burn. The fuels were exposed to the wind; there was no cloud cover. There was incomplete weather data available for the burn site, but no rain the week before the burn and the weather pattern was holding.

FUEL MODEL PARAMETERS
****

Fuel Model 60

Load (T/AC)		S/V Ratios		Other	
1 hr	1.61	1 hr	1689.	depth	1.0
10 hr	1.20	live herb	1300.	heat content	8227.
100 hr	.63	live woody	1300.	ext moisture	34.
live herb	.09				
live woody	.93	wind adjustment factor:		.5	

Fuel Model 61

Load (T/AC)		S/V Ratios		Other	
1 hr	1.71	1 hr	2689.	depth	.88
10 hr	.83	live herb	700.	heat content	8172.
100 hr	.39	live woody	700.	ext moisture	34.
live herb	.08				
live woody	.92	wind adjustment factor:		.5	

Fuel Model 62

Load (T/AC)		S/V Ratios		Other	
1 hr	2.74	1 hr	2246.	depth	.91
10 hr	.97	live herb	2800.	heat content	8557.
100 hr	.45	live woody	1300.	ext moisture	30.
live herb	.29				
live woody	1.06	wind adjustment factor:	.5		

SITE ENVIRONMENTAL PARAMETERS

Observ. No.	Date	Time	Slope	Aspect	20-ft Wind Vector	Dir. of Wind	Dry Bulb (F)	RH	Dir. of ROS Calc.
1	9/28	1335	30	w	12	0	66	31	max
2	9/28	1426	30	w	14	0	66	31	max
3	9/28	1457	30	w	12	0	64	32	max
4	9/28	1512	35	w	14	0	61	33	max
5	9/28	1517	35	w	12	350	61	33	max
6	9/28	1522	35	w	12	10	63	37	max
7	9/28	1531	35	w	12	0	64	35	max
8	9/29	1230	30	w	14	270	63	32	max
9	9/29	1245	30	w	12	270	63	32	max
10	9/29	1255	30	w	14	270	63	32	max

FIRE BEHAVIOR OBSERVATIONS

Observation Number	ROS (ch/hr)	Flamelength (ft.)
1	13.6	5
2	18.0	8
3	13.6	5
4	48.0	8
5	20.5	5
6	18.3	8
7	35.9	8
8	30.0	6
9	46.4	8
10	60.0	7

WALDEN BURN
****

Custom Fuel Model from NEWMDL:

Model 65--fuels: sagebrush, with 60% area coverage, 30% leaves and live twigs

GENERAL SITE PARAMETERS
****

The Walden prescribed burn occurred in Colorado on October 7. Fuels were exposed to the wind. There was incomplete weather data for the site--there was no rain the week before the burn and the weather pattern was holding. There was no slope.

FUEL MODEL PARAMETERS
****

Fuel Model 65

Load (T/AC)		S/V Ratios		Other	
1 hr	5.75	1 hr	1200.	depth	2.4
10 hr	1.44	live herb	0.	heat content	8731.
100 hr	2.87	live woody	1000.	ext moisture	35.
live herb	.00				
live woody	4.31	Wind adjustment factor:		.6	

SITE INPUT
****

Observ. No.	Time	20-ft. Wind	Dry Bulb	Rh	Burn Time Cloud Cover	Dir. for ROS Calculations
1	1323	0	69	33	0	max
2	1339	0	65	31	5%	max
3	1516	20	72	28	0	315
4	1218	23	65	31	2	180
5	1334	12	63	32	40	135
6	1339	10	65	31	40	135
7	1402	8	64	31	40	max
8	1510	23	72	28	10	max
9	1513	33	66	35	15	max

FIRE BEHAVIOR OBSERVATIONS
****

Observation Number	ROS (ch/hr)	Flamelength (ft)
1	1.1	2-5
2	2.3	6-20
3	10.9	9-15
4	.9	5.5-15
5	.9	12-15
6	.8	1.5-3
7	2.6	10
8	36.4	unavailable
9	45.5	unavailable

BEAR TREE BURN
****

Custom Fuel Model from NEWMDL:

Model 70: Fuels--
Grass; 10% coverage,1 foot deep, 100% 1 hrtl, 100% dead
Litter; 30% coverage, Ponderosa Pine, 4 inches deep, all 1 hrtl.
Slash; 55% coverage, from pre-commercial thinning, 2 yrs. old, avg. DBH 7 inches, 1 1/2 feet deep.

GENERAL SITE DESCRIPTION
****

This burn occurred in Colorado on October 21. Fire spread through observation point 2 was primarily in grass and litter. Fire spread through points 1,3,6 was in light slash (like NFFL model 11). Fire spread through points 4,5 was through medium slash like NFFL model 12. Weather data was incomplete for the week before the burn, but the weather pattern was holding.

FUEL MODEL PARAMETERS
****

Fuel Model 70

Load (T/AC)		S/V Ratios		Other	
1 hr	8.35	1 hr	2510.	depth	.72
10 hr	5.48	live herb	0.	heat content	8497.
100 hr	2.84	live woody	2300.	ext moisture	12.
live herb	.00				
live woody	.05	Wind adjustment factor:		.5	

SITE INPUT
****

Observ. No.	Time	Hand-held Anemometer Windspeed	Dry Bulb (F)	RH	Dir. for ROS Calc.
1	1231	7-9	63	36	180
2	1335	7	64	23	max
3	1406	3	61	20	225
4	1426	2	61	23	max
5*	1518	6**	62	28	max
6	1601	8	65	31	max

* For this point slope was 15%, the aspect was west.
** This windspeed value was fire influenced. Direction of the wind vector was 0.

FIRE BEHAVIOR OBSERVATIONS

****

Observation No.	ROS (ch/hr)	Flamelength (ft)
1	.6	3-4
2	4.6	4-5
3	1.0	3
4	1.5	4-5
5	3.6	4-7
6	1.7	6-8

APPENDIX B

Fire Behavior Observations and Predictions

Appendix B

Fire Behavior Observations and Predictions

Bates Creek

Rate of Spread CH/HR

Observed	Predicted Model 20	21	22	5
1. 9.1	2	1	8	14
2. 13.6	2	1	8	14
3. 1.8	0	1	1	2
4. 25.3	6	1	10	21
5. 16.4	8	3	11	27
6. 6.8	8	3	11	27
7. 20.5	8	3	11	27
8. 20.5	8	3	11	27
9. 20.5	8	3	11	27
10. 5.2	1	0	0	1
11. 7.5	1	1	12	27
12. 8.7	3	6	9	28

Flamelength FT.

Observed	Predicted Model 20	21	22	5
1. 4.5	.7	.3	2.3	3
2. 5.0	.7	.3	2.3	3
3. 2.5	.3	.4	.8	1.7
4. 5.0	1.2	.3	2.6	4.3
5. 2.5	1.5	.8	2.9	5.9
6. 6.0	1.5	.8	2.9	5.9
7. 3.0	1.5	.8	2.9	5.9
8. 3.0	1.5	.8	2.9	5.9
9. 3.0	1.5	.8	2.9	5.9
10. 4.5	.3	.3	.8	1.6
11. 6.0	.6	.3	2.9	1.6
12. 5.0	.8	1.1	2.7	6.2

Summary of Results of Regression Analysis

Fuel Model	Correlation Coefficient R-squared		Y intercept		Slope	
	ROS	Fl	ROS	Fl	ROS	Fl
20	23.6	7.0	7.96	4.94	1.68	-.998
21	3.6	7.8	11.1	4.89	.865	-1.25
22	36.0	2.2	3.29	3.57	1.13	.249
5	28.7	6.0	4.94	4.87	.399	-.165

Martin-Marietta

The Forest Service modeled this burn using NFFL model 6 for Oakbrush fuels and NFFL 9 for the Mountain Mahogany. We made SITE runs for the custom models 30 and 31 and also for NFFL models 6 and 9. We also did SITE runs using the two fuel model concept to incorporate the grass fuels with the NFFL models. Custom model 30 corresponds to the Oakbrush fuels and model 31 was built up from Mountain Mahogany data. We used NFFL model 1 to represent the grass fuels when using the two fuel model concept.

There were no recorded observations of fire behavior, because of low, sporadic fire spread. We speculate that fuels at the time of burning were at or near their moisture of extinction, even though the models gave no hint that combustion would be difficult to sustain.

Rate of Spread

	Predictions						
Model 30	6	30+1	6+1	31	9	31+1	9+1
35	37	72	61	1	10	32	46
93	77	149	146	0	24	69	117
83	70	150	142	1	21	70	116
82	69	147	139	0	21	69	113
38	38	78	64	1	10	33	69
30	27	56	41	1	7	21	65

Flamelength

	Predictions						
Model 30	6	30+1	6+1	31	9	31+1	9+1
8.5	6.5	5.3	4.7	.9	3.2	4.3	4.8
13.0	8.8	7.1	7.1	.3	4.6	6.0	7.2
12.4	8.4	7.1	7.1	.8	4.4	3.5	3.9
12.3	8.3	4.7	3.8	.3	4.3		
8.7	6.4			.8	3.2		
7.6	5.6			.7	2.7		

We compared predictions from the NFFL fuel models with the custom models by regressing the predictions from the appropriate NFFL model with the predictions of the custom model that most closely matched it.

R-squared Values from Custom/NFFL comparisons

Model	30/NFFL 6	30+1/6+1	31/9	31+1/9+1
ROS	99.0	99.8	55.4	88.0
FL	99.0	100.0	39.9	99.7

The custom model predictions appear to closely match predictions made with the NFFL models, but this is only an indication that the Forest Service chosen NFFL models were appropriate for perceived fuelbed and environmental conditions, not an indication that they accurately represented the fuels on the site at the time of the attempted burn.

Wintersteen

Observed ROS		Predicted Model 50	51	52
1.6	w/ wind	RH 31- 20	10	13
		RH 25- 20	10	13
	backing	RH 31- 2	2	2
		RH 25- 2	2	2

Observed Fl		Predicted Model 50	51	52
4.13	(same env-	6.4	4.2	5.0
	ironmental	6.3	4.1	4.9
	changes	2.4	1.9	2.2
	used)	2.4	1.9	2.2

We did not do a regression analysis for this burn because of the lack of actual fire behavior observations.

Berry Creek

Rate of Spread

Observed	Predicted Model 60	61	62
1. 13.6	18.0	48.0	18.0
2. 18.0	22.0	60.0	39.0
3. 13.6	18.0	48.0	32.0
4. 48.0	22.0	60.0	40.0
5. 20.45	19.0	48.0	32.0
6. 18.3	18.0	48.0	32.0
7. 35.9	18.0	48.0	32.0
8. 30.0	19.0	54.0	34.0
9. 46.4	16.0	45.0	unavailable
10.60.0	19.0	54.0	unavailable

Flamelength

Observed	Predicted Model 60	61	62
1. 5.0	6.4	8.6	6.4
2. 8.0	7.0	9.6	10.0
3. 5.0	6.4	8.6	9.0
4. 8.0	7.0	9.6	9.9
5. 5.0	6.4	8.6	9.1
6. 8.0	7.0	8.6	8.9
7. 8.0	6.4	8.6	9.0
8. 7.0	6.4	8.9	9.2
9. 8.0	5.9	8.2	unavailable
10.7.0	6.4	8.9	unavailable

Summary of Results of Regression Analysis

Fuel Model	Correlation Coefficient R-squared		Y intercept		Slope	
	ROS	Fl	ROS	Fl	ROS	Fl
60	.1	3.8	25.6	1.49	.253	.836
61	5.6	10.6	-6.77	-1.75	.725	.981
62	28.6	33.4	-6.96	-.188	.979	.776

Walden

Observed ROS	Model 65 Predicted	Observed Flamelength	Model 65 Predicted
1. 1.1	2	2-5	5.3
2. 2.3	2	6-20	5.5
3. 10.9	41	9-15	19.9
4. .9	2	5-15	4.6
5. .9	2	12-15	4.8
6. .8	2	1.5-3	4.8
7. 2.6	28	10	16.2
8. 36.4	92	unavailable	28.7
9. 45.5	122	unavailable	31.4

Summary of Results of Regression Analysis

Model 65	Correlation Coefficient R-squared		Y intercept		Slope	
	ROS	Fl	ROS	Fl	ROS	Fl
	96.6	22.5	-.999	4.02	.376	.292

This model predicted rate of spread well, but not flamelength--a recurring problem found in testing the models, making one model hard to refine for predicting both ROS and flamelength.

Bear Tree

Observed	Predicted Model 70	NFFL 2	11	12
ROS				
1. .6	2	2	1	1
2. 4.6	16	23	5	11
3. 1.0	10	19	4	9
4. 1.5	6	8	3	6
5. 3.6	20	31	6	12
6. 1.7	32	52	8	17
Flamelength				
1. 3	1.8	1.7	1.1	2.8
2. 4	5.3	5.2	3.2	7.4
3. 3	3.7	4.4	2.6	6.4
4. 4	3.4	3.3	2.4	5.7
5. 4	5.9	5.9	3.4	7.6
6. 6	7.4	7.5	4.0	8.9

Summary of Results of Regression Analysis

Fuel Model	Correlation Coefficient R-squared ROS	Fl	Y-intercept ROS	FL	Slope ROS	Fl
70	15.6	71.7	1.34	1.88	.0575	.462
2	10.4	64.2	1.53	1.98	.0286	.433
11	21.0	61.0	.831	1.68	.297	.852
12	21.3	55.7	.926	1.49	.133	.389

We included some testing of representative NFFL models. This comes in handy for comparing different fuel inputs when a NFFL model predicts more accurately than the custom model. The models on this burn consistently predicted flamelength better than they predicted rate of spread. This will present the same problems as in Walden when trying to get one fuel model to predict both flame length and rate of spread. If Bear Tree and Walden were both in the same fuel type, then their results could complement each other when trying to refine a fuel model to predict both rate of spread and flamelength.

APPENDIX C

Sensitivity Tabulations for Fuel Model 20

Appendix C

Sensitivity Tabulations for Fuel Model 20

ROS/FL Input	Model 20 Value	Sensitivity Range
SA1	(2679 ft^{-1})	2.4<ROS/FL<5.1 for 192<SA1<743 5.1<ROS/FL<7.6 for 743<SA1<3500
SAH	(2800 ft^{-1})	5.8>ROS/FL>4.6 for 192<SAH<1200 6<ROS/FL<6.9 for 1200<SAH<3500
SAW	(2300 ft^{-1})	6.2>ROS/FL>5 for 192<SAW<1200 6.8>ROS/FL>6.2 for 1200<SAW<1295 6.2<ROS/FL<7.4 for 1295<SAW<3500
L1	(.19 T/A)	1.9>ROS/FL>1.1 for .001<L1<.02 1.1<ROS/FL<6.5 for .02<L1<.19 6.5>ROS/FL>4 for .19<L1<5.8 ROS/FL = 4 for 5.8<L1<14 4<ROS/FL<6.3 for 14<L1<30
L10	(.13 T/A)	7>ROS/FL>2 for .001<L10<5 2>ROS/FL>.8 for 5<L10<30
L100	(.03 T/A)	6.6>ROS/FL>2.2 for .001<L100<5 2.2>ROS/FL>1.7 for 5<L100<30
LH	(.11 T/A)	6.6>ROS/FL>2.2 for .001<LH<.83 2.2>ROS/FL>.3 for .83<LH<18 ROS/FL = .8 for 18<LH<30
LW	(.23 T/A)	6.2>ROS/FL>.4 for .001<L1<5 ROS/FL = .4 for 5<LW<30
DEPTH	(.4 ft)	0<ROS/FL<13 for .01<DEPTH<1.7 13<ROS/FL<29 for 1.7<DEPTH<10
EXTM	(18%)	2.5<ROS/FL<3.1 for 10<EXTM<13 3.1<ROS/FL<6.5 for 13<EXTM<18 ROS/FL = 6.6 for 18<EXTM<60

Input	ROS (ft/min) Sensitivity Range	FL (ft) Sensitivity Range
SA1	0<ROS<6 for 192<SA1<743 6<ROS<13 for 743<SA1<3500	.28<FL<1.2 for 192<SA1<743 1.2<FL<1.7 for 743<SA1<3500
SAH	7>ROS>5.5 for 192<SAH<1200 10<ROS<11 for 1200<SAH<3500	1.2>FL>1.1 for 192<SAH<1200 FL = 1.6 for 1220<SAH<3500
SAW	6>ROS>5 for 192<SAW<1200 11>ROS>9.8 for 1200<SAW<2400 9.8<ROS<11 for 2400<SAW<3500	1>FL>.9 for 192<SAW<1200 1.7>FL>1.5 for 1200<SAW<3500
L1	0<ROS<28 for .001<L1<5 28>ROS>11 for 5<L1<30	0<FL<6.7 for .001<L1<5 6.7>FL>1.6 for 5<L1<30
L10	10>ROS>5.4 for .001<L10<1 ROS = 5.4 for 1<L10<4 5.4<ROS<5.7 for 4<L10<7.1 5.7>ROS>1 for 7.1<L10<30	1.4<FL<3.6 for .001<L10<8.3 FL = 3.6 for 8.3<L10<10.3 3.6>FL>1.8 for 10.3<L10<30
L100	11>ROS>3.5 for .001<L100<2 3.5>ROS>.8 for 2<L100<30	1.5>FL>1.1 for .001<L100<3 1.1<FL<1.7 for 3<L100<14 1.7>FL>.7 for 14<L100<30
LH	8.7<ROS<10 for .001<LH<.14 10>ROS>.1 for .14<LH<.28 .1>ROS>0 for .29<LH<30	1.3<FL<1.6 for .001<LH<.14 1.6>FL>.26 for .14<LH<.28 .26>FL>.1 for .28<LH<5 .1>FL>0 for 5<LH<30
LW	8.7>ROS>0 for .001<LW<1.6 ROS = 0 for 1.6<LW<30	1.2>FL>.1 for.001<LW<5 .1>FL>0 for 5<LW<30
DEPTH	0<ROS<29 for .01<DEPTH<1.7 29<ROS<86 for 1.7<DEPTH<10	0<FL<2.2 for .01<DEPTH<1.7 2.2<FL<3 for 1.7<DEPTH<10
EXTM	0<ROS<1.7 for 10<EXTM<13 1.7<ROS<10 for 13<EXTM<18 10<ROS<12 for 18<EXTM<60	.26<FL<.35 for 10<EXTM<13 .35<FL<1.6 for 13<EXTM<18 1.8<FL<1.9 for 18<EXTM<60